

Restrictions to the application of ‘diagnostic’ criteria for recognizing ancient seismites

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Abstract Soft-sediment deformation structures induced by seismic liquefaction and/or fluidization receive much attention in sedimentological, structural and palaeoseismic studies. The direct record of larger earthquakes is restricted to instrumental and historical data; the recognition of prehistoric earthquakes requires criteria to recognize seismites in the geological record. The areal distribution of seismites can sometimes be related to active faults since distances to the epicenter (for a given magnitude) tend to be related to the liquefaction effects of seismic shocks.

The use of soft-sediment deformation structures for palaeoseismic studies has limitations, however. Hardly anything is known, for instance, about the effects that modern seismic events have on the sediments in most environments. Moreover, criteria for the recognition of seismites are still under discussion. The following characteristics seem, particularly in combination, the most reliable: (1) Soft-sediment deformation structures should occur in laterally continuous, preferably recurring horizons, separated by undeformed beds; (2) These deformation structures should be comparable with structures known to have been triggered by modern seismic activity; (3) The sedimentary basin should have experienced tectonic activity at the time when the deformations were formed; and (4) The intensity or abundance of the soft-sediment deformation structures in a presumed seismite should change laterally, depending on the distance to the epicenter. It turns out that all of these four criteria have important exceptions. (1) Soft-sediment deformation structures occurring over large lateral distances in a specific layer can be triggered also by other processes. Moreover, in environments with a low sedimentation rate, the time between successive earthquakes is often too short to allow accumulation of beds that remain undisturbed. Furthermore, total liquefaction of a sandy bed may result in the absence of deformation features. (2) No truly diagnostic soft-sediment deformation structures exist to prove seismic activity. Moreover, the final configuration of a soft-sediment deformation structure is independent of the type of trigger. (3) Seismites occur frequently in areas where seismic activity is low today. (4) The lateral changes in the intensity of soft-sediment deformation structures in seismites as a factor presumed to depend on the distances to the epicenter, pose a complicated problem. The 2012 Emilia earthquakes, for instance, affected sandy fluvial channels but not the fine-grained floodplains.

It must thus be deduced that specific soft-sediment deformation structures cannot be used without additional evidence to identify seismites. In particular, the magnitude of seismic shocks and the recurrence time of main events (the most important features that allow recognition of seismites) seem to be sedimentological in nature: facies changes in space and time seem the

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parameters that most strongly control the occurrence, morphology, lateral extent and the vertical repetition of seismites.

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1 Introduction

Soft-sediment deformation structures (SSDS) record sedimentary and tectonic processes in most depositional environments as far as they occurred during/after sedimentation and before complete lithification. In particular, SSDS induced by earthquakes can do so regarding tectonic activity. It is worthwhile mentioning here that Seilacher (1969, 1984) named layers with tectonically-induced SSDS 'seismites', but that this term later was, unfortunately, commonly used for technically-induced deformation structures. Nowadays, the term is again commonly used in its original sense, *i.e.* in the sense of layers (or sets of layers) that are characterized by the abundant occurrence of seismically triggered SSDS (Ricci-Lucchi and Amorosi, 2003; Neuendorf *et al.*, 2005); this is much more logical, as most types of SSDS can be found in seismites (in its original sense), so that these deformation structures are no indication of seismic activity in themselves. Extensive layers with such structures being present over large lateral distances are much more diagnostic, but it should be realized that it may be difficult in practice to prove that the deformations were seismically induced. The reason is that no truly diagnostic features exist, and that the combinations of features which are commonly considered as strong evidence, can be misleading. This problem will be detailed in the present contribution.

Seismites receive much attention from geologists since they represent the best records of ancient earthquakes. They have been reported in sediments ranging in age from Palaeoproterozoic (Mazumder *et al.*, 2006) (Figure 1) and Meso-Neoproterozoic (Pratt, 1994; Owen, 1995; Van Loon and Su, 2013) to the Recent (Figure 2). Seismites seem to be ubiquitous, having been reported from almost all sedimentary environments (*cf.*, Van Loon, 2009), but particularly from continental ones: (1) lacustrine (Sims, 1973, 1975; Davenport and Ringrose, 1987; Alfaro *et al.*, 1997; Moretti and Ronchi, 2011), including (2) glaciolacustrine (Gruszka and Van Loon, 2007; Van Vliet-Lanoë *et al.*, 2010) and (3) playas (Mountney and Jagger, 2004); (4) fluvial (Jones, 1962; Allen and Banks, 1986; Owen, 1995;

Alfaro *et al.*, 1999); (5) eolian (Horowitz, 1982; Moretti, 2000; Moretti *et al.*, 2002), including (6) ergs (Netoff, 2002) and (7) caves (Kos, 2001). They are, however, also known, particularly in ancient rocks, from (8) transitional environments (Plint, 1983) and from full-marine environments, including (9) upper shoreface (Seilacher, 1969; Rascoe, 1975); (10) foreshore (Montenat, 1980); (11) offshore (Van Loon *et al.*, 2008), including (12) shelf slope (Rindente and Trincardi, 2006), (13) deep-marine (Long, 2004) and (14) pelagic deposits (Haczewski, 1986). Not surprisingly, they have been frequently described from (15) various types of tectonically affected environments such as syn-rift regions (Jackson *et al.*, 2005; Rodríguez-Lopez *et al.*, 2007) and (16) turbidite-dominated environments (Roep and Everts, 1992). Most seismites have been described from siliciclastic successions, but deformational structures attributed to seismic liquefaction and/or fluidization have also been reported from shallow-marine carbonate successions (Cisne, 1986; Pratt, 1994; Pope *et al.*, 1997; Spalluto *et al.*, 2007; Mastrogiacomo *et al.*, 2012). The occurrence of SSDS induced by seismic liquefaction has been assumed even on Mars (Metz *et al.*, 2010). Palaeoseismic studies have been carried out in Holocene sedimentary successions through the analysis of liquefaction and fluidization structures related to historical events (Charleston area and New Madrid seismic zone; Obermeier *et al.*, 1990).

Seismic liquefaction processes have been connected to seismic shocks with $M > 5$ (Ambraseys, 1988) and with critical acceleration depending on the actual magnitude of the earthquakes (for $M = 5$, $a = 0.20$ g; for $M = 8$, $a = 0.03$ g; Carter and Seed, 1988). Seismic liquefaction effects are mainly located within a maximum distance of 40 km from the epicenter (more than 90% of recent seismic events; Galli, 2000). The type and dimension of seismites have been interpreted as a function of the magnitude of palaeo-earthquakes (Guiraud and Plaziat, 1993; Rodríguez Pascua *et al.*, 2000), and their spatial distribution can be used to locate main active faults (Alfaro *et al.*, 2010). Insight into the development of seismites in the geological past was deepened by experiments during which they were reproduced in the laboratory with dif-



Figure 1 Seismite in a shallow-marine Paleoproterozoic quartzite (Chaibasa Formation) in East India. The seismite can be traced from exposure to exposure over many kilometers.

ferent methodologies, including shaking tables (Owen, 1992; Moretti *et al.*, 1999); these experiments were performed mainly in order to increase the understanding of which particular seismic and sedimentary features trigger liquefaction.

In the following, we will describe some field examples of ancient and present-day seismic liquefaction features, results from laboratory studies and procedures that may help recognize seismically-induced SSDS. The objective is to delineate the problems related to the recognition of seismites for palaeoseismic studies. In particular, we show how detailed knowledge of the parameters that trigger the formation of seismites can contribute to outline the limitations and reliable application of seismically-induced soft-sediment deformation structures in palaeoseismic studies.

2 Standard procedures for the recognition of seismites

Most SSDS are induced by liquefaction and fluidization (Allen, 1982). These processes occur frequently in a wide variety of sedimentary environments and are related to numerous trigger processes; examples are, to mention only a few, overloading (Moretti *et al.*, 2001), storm waves (Molina *et al.*, 1998; Alfaro *et al.*, 2002), sudden fluctuations in the groundwater table (Guhmann and Pederson, 1992; Holzer and Clark, 1993), karst activity (Moretti *et al.*, 2011), tsunamis (Mazumder *et al.*, 2006; Cita, 2008; Shiki *et al.*, 2008) and tidal activity (Greb and Archer, 2007).

The final morphologies of SSDS resulting from liquefaction and fluidization (Figure 3) depend mainly on the

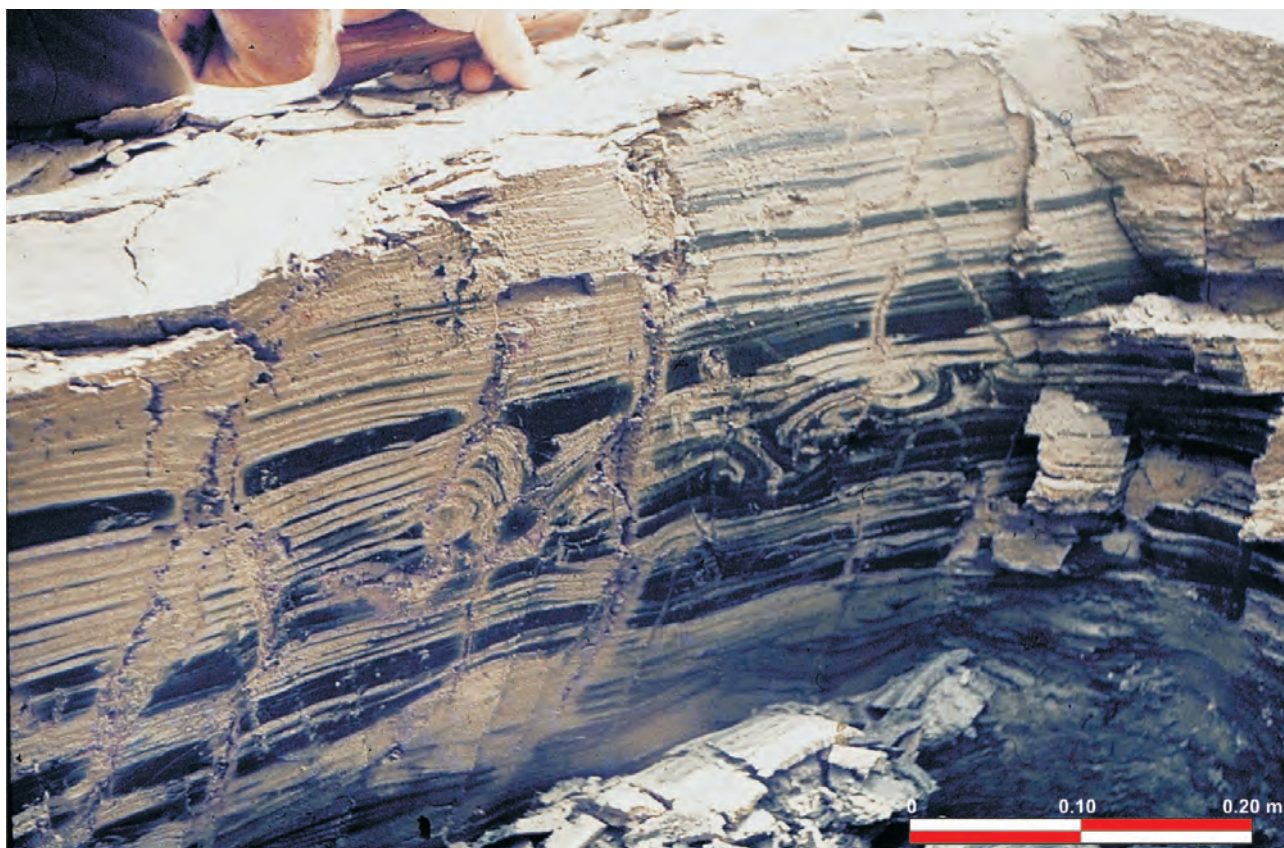


Figure 2 Modern 'estuarine' sediments in the Bay of Mont St. Michel (Normandy, France), showing deformations triggered by a seismic shock in the middle of the last century.

initial sedimentary setting, the driving force and the duration of the deformable state, whereas the nature of the trigger mechanism seems to play a negligible role (Owen and Moretti, 2011; Owen *et al.*, 2011). In other words, SSDS can have identical morphologies, independent of whether they were formed due to a seismic shock or by other trigger mechanisms (cf., Van Loon, 2009).

Presumed diagnostic criteria

In order to cope with this problem, several authors have tried to identify criteria which might allow seismically-induced SSDS to be distinguished from deformations caused by other trigger mechanisms. In his pioneering work, Sims (1975) stated that seismites could be recognized as such if (1) they occur in a seismically active region, (2) the SSDS are largely restricted to specific stratigraphic horizons, (3) they can be traced or correlated over large areas within a sedimentary basin, and (4) there is no detectable influence of slope movement or failure.

Obermeier *et al.* (1990) suggested that only sand blows be used for palaeoseismic studies. To recognize seismically-induced sand blows, they mentioned the following criteria: (1) evidence for an upward-directed, strong hy-

draulic force that acted suddenly and only briefly; (2) the features must have sedimentary characteristics that are consistent with historically documented observations of earthquake-induced liquefaction processes; (3) they are not associated with artesian springs; (4) they occur at multiple locations (within a few kilometers of one another) and are separated by long time intervals during which no such features formed.

Hilbert-Wolf *et al.* (2009) suggested the following criteria by summarizing some studies on the same topic (Obermeier, 1996; Rossetti, 1999; Wheeler, 2002): (1) a clear association with faults as potential triggers, (2) the observed deformations must be consistent with those having a known seismic origin, (3) a widespread occurrence that is temporally constrained, (4) a systematically higher intensity or increase in frequency towards a possible epicenter, (5) lack of indications for any other causal mechanisms, (6) vertical recurrence of deformed layers, (7) a stratigraphic position in between undisturbed layers, and (8) the presence of faults associated with wedges of intraformational breccias, conglomerates, or massive sandstones.

More recently, Owen and Moretti (2011) proposed the



Figure 3 Characteristic morphology of liquefaction-induced SSDS in a Warthanian/Eemian (Late Pleistocene) seismite in lacustrine sediments at Siekierki (northwestern Poland). The responsible seismic shock was probably due to glacio-isostatic rebound after deglaciation; the term ‘deglaciation seismotectonics’ was used by Muir-Wood (2000) for such tectonics.

following criteria to recognize seismites: (1) a large areal extent; (2) lateral continuity of deformed sediment; (3) vertical repetition; (4) SSDS with a morphology comparable with structures described from earthquake-affected layers; (5) proximity to active faults; (6) correlation between complexity or frequency with distance from the triggering fault.

This brief review shows how criteria have changed, and increased and/or decreased in relevance over time; in the next sections it will be pointed out why some of these criteria cannot be ascribed exclusively to seismic activity and how they can lead to incorrect conclusions.

3 Limitations

Studies aimed at the recognition of seismites are confronted with some important obstacles as none of the criteria mentioned above is diagnostic in itself, and because non-seismic processes may result in layers with comparable SSDS. The main obstacles are the subject of this section.

3.1 The actualism criterion

The first criterion that cannot be applied directly to the study of seismites is the actualism criterion, although the visionary statement by Geikie, based on the earlier ‘discovery’ by Hutton of the uniformitarian (later called ‘actualism’) principle, that “the present is the key to the past” is applicable to most sedimentary structures. In fact, present-day seismically-induced liquefaction has been directly observed only in very rare cases, and the resulting structures have been studied in only few continental environments (mostly floodplains and intertidal areas). Consequently, there is insufficient direct data on what happens in soft and water-saturated sediments within shallow-marine and lacustrine environments (that comprise the great majority of the ancient seismites reported in literature) to unravel in detail how SSDS are formed in specific layers (seismites) during a seismic event.

In addition, it should be realized that seismic deformation processes (and particularly those due to liquefaction)

in floodplains, lake-marginal areas and intertidal environments are not necessarily similar to those which may take place in other sedimentary environments: liquefaction in floodplains typically involves buried sedimentary units located below the groundwater table (as a rule less than 9 m deep; deeper layers are hardly ever deformed by seismic shocks); these buried but still unconsolidated and water-saturated sedimentary units should be susceptible to liquefaction and preferably be overlain by a layer with more restricted permeability.

Complete liquefaction can induce fluidization of fine-grained particles that then will try to escape into the direction of the lowest pressure (= upwards), thus looking for an upward pathway. If the overlying sediment has zones of weakness or if they fail under the pressure exerted by the pressurized pore-water/sediment mixture, this mixture may intrude the overlying unit(s), forming one or more sedimentary dykes and venting features (sand or mud volcanoes) at the sediment/air interface. The deformational conditions are very different for soft sediments that are susceptible to liquefaction while still located at the water/sediment interface: they are always water-saturated and their shear strength is much (sometimes orders of magnitude) lower than that of a sedimentary unit buried under 5–7 m of younger sediments. The processes and products related to ancient earthquakes and developed in deeper lacustrine and marine environments can therefore be estimated only theoretically and can be reconstructed with some accuracy only by means of analog experiments in the laboratory (Moretti *et al.*, 1999).

3.2 Lateral extent of seismites

This criterion is based on the observation that in the case of moderate- to high-magnitude earthquakes ($M > 5$), though depending on the nature of the affected sediments, the threshold for seismically-induced liquefaction results in liquefaction that affects large areas (as a rule, an area within 40 km from the epicenter). There are, however, also other geological processes that are able to produce deformation of soft sediments over large areas, as shown by Greb and Archer (2007) for tidal flats; it may also be assumed that other processes can make sediments liquefy in extensive areas, for example storm waves (resulting in cyclical loading), and instability due to overloading such as can be induced by sedimentation on a prograding delta.

It may in practice be impossible to trace a seimite over a long distance (Figure 4): it may be tectonically disturbed; it may have been eroded away locally; it may be on a property where access is denied; it may be covered by vegeta-

tion, or be unexposed for any other reason. This may prevent establishing lateral continuity. But even if a layer is exposed over long distances, it should be kept in mind that the lateral continuity of seismites is largely controlled by the distribution of the sedimentary units involved. Layers may, for instance, wedge out and have lateral equivalents that are less susceptible to liquefaction because of a different grain-size distribution and/or a different degree of compaction; lateral facies changes seem to strictly control the areal extent of seismic liquefaction effects (Alfaro *et al.*, 2010). This finding is consistent with observations carried out in the field after modern earthquakes: the massive liquefaction effects reported from the recent (20–29 May 2012) Emilia earthquakes (Ninfo *et al.*, 2012; Emergeo Working Group, 2013), which are reflected in the occurrence of sand-volcanoes and dykes (Figure 5), are present only in buried and active channel and levee deposits; laterally, fine-grained overbank deposits with a low susceptibility to seismic liquefaction do not show any liquefaction effects.

Distinct lateral facies changes are not a prerequisite, however, for changes in the intensity of liquefaction. Even in the absence of evident lateral facies changes, studies on seismic liquefaction carried out with different methods (De Alba *et al.*, 1976; Moretti *et al.*, 1999; Finn, 2001) show how small changes in grain size, matrix content, porosity, water content, *etc.*, can drastically decrease the susceptibility to liquefaction of a sedimentary unit.

3.3 Vertical repetition

In his pioneering works, Sims (1973, 1975) calculated the average time of recurrence for moderate- to high-magnitude earthquakes in the Los Angeles area (California) on the basis of sedimentation rate and the number of deformed beds in the lacustrine succession that he investigated. It has become clear in the meantime, however, that the outcome of such an approach may suffer from a series of errors.

The first possible error is due to a simple fact: not all seismic events leave a trace in the sedimentary record in the form of liquefaction-induced SSDS. The second possible error stems from the fact that the occurrence of SSDS requires the presence of a driving force system acting on the sedimentary units involved; this driving force tends to cause visible deformations (like load-casts in a layer or sets of layers with a reversed density gradient), but sometimes complete liquefaction of a sedimentary unit takes place without inducing any appreciable deformation (Moretti *et al.*, 1999). In other words, it is highly probable that sedi-

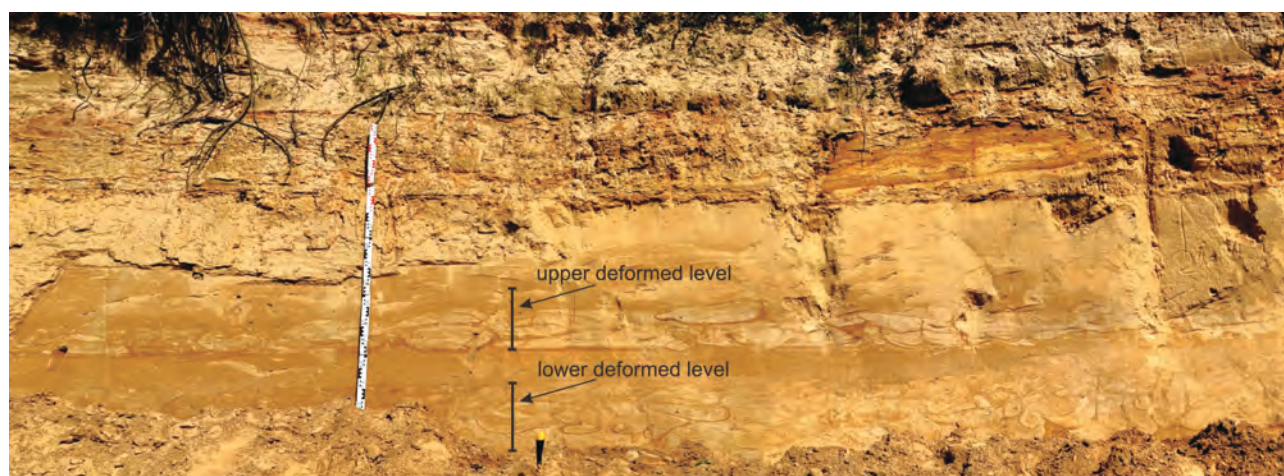


Figure 4 Section at Siekierki (northwestern Poland) with two strongly deformed layers (seismites) interbedded between undeformed lacustrine sediments. Photo courtesy Dr. M. Pisarska.

mentary successions formed in a tectonically active area show a record of seismic shocks that is incomplete, thus not representing all shocks that actually occurred in the area. It can easily be hypothesized that many seismites therefore never have been recognized as such. It is equally possible that only one layer shows all characteristics of a seismite, but is not interpreted as such because a tectonically active situation cannot be proven.

On the other hand, Gibert *et al.* (2011) described some field examples where clearly only one single seismic shock induced liquefaction in several superimposed deformed beds: such a situation may in less distinct cases lead to an overestimation of the number of seismic shocks. Furthermore, the presence of lateral facies changes and erosive surfaces can cause dramatic lateral changes in the number and thickness of superimposed deformed beds. All palaeoseismic analyses should therefore include a detailed study of all individual deformed beds, which should preferably be carried out in a large number of trenches that allow the analysis of the lateral changes.

3.4 Relationships between morphology/size of seismites and earthquake magnitude

Numerous studies on the characteristics of seismites suggest a direct relationship between the type and intensity of seismites and the magnitude of the responsible seismic shocks. For example, Rodríguez Pascua *et al.* (2000) interpret each single kind of SSDS as induced by variable seismic intensity. This cannot be true, however, as it turns out that almost all types of liquefaction-induced SSDS can occur closely together; only their size, complexity and intensity change laterally, depending on the distance from

the epicenter. Also this type/distance relationship can be difficult to establish, as all studies on SSDS show that the final morphologies are related strongly to the characteristics of the initial sediment, the driving force acting during deformation, and the duration of a deformable state. Furthermore, experiments carried out on seismically-induced SSDS (Moretti *et al.*, 1999) show that the final morphologies are independent of the acceleration (and magnitude) of the earthquakes.

The thickness of the sedimentary unit(s) involved in seismically-induced liquefaction seems to be unrelated to the magnitude of seismic shocks, too. This was detailed by Alfaro *et al.* (2010), who described giant seismites from an area in southern Spain that was affected by earthquakes of moderate magnitude; these seismites showed clearly that the thickness of the seismically-deformed sedimentary unit(s) is related only to the thickness of the sedimentary unit(s) susceptible to liquefaction.

4 The recognition of a seismic trigger

Owen *et al.* (2011) has suggested a three-stage approach to identify the trigger mechanisms for SSDS. These are facies assessment, trigger assessment and criteria assessment.

4.1 Facies assessment

Detailed facies analysis of the entire sedimentary succession involved in the deformation will, as a rule, help to establish correct relationships between depositional features and the occurrence of SSDS. This is important because endogenic and exogenic factors can thus be dis-



Figure 5 Sand blows formed after the 2012 Emilia earthquake in Italy, indicating pore-water escape and liquefaction/fluidization, which must have resulted in the formation of SSDS of a buried layer, which consequently should be considered as a seismite (from Emergeo Working Group, 2012).

tinguished. SSDS resulting from endogenic triggers (overloading, storm wave action, *etc.*) obviously will occur in a given facies repeatedly over time; for exogenic triggers (earthquakes, tsunamis, impacts, *etc.*), a much weaker relationship exists. Examples of this approach have been provided by Moretti and Ronchi (2011), Owen and Moretti (2011) and Oliveira *et al.* (2011).

4.2 Trigger assessment

When it has been determined if the formation of SSDS in a specific layer was triggered by an exogenic process, a trigger-by-trigger assessment of the evidence can be

undertaken to identify the most likely trigger. For this purpose, the various SSDS have to be studied in detail in order to unravel the various processes that were involved in the deformation, and determine the role of grain-size differences in the deformational process. Also the state of the sediment during deformation (fully water-saturated, degree of compaction and early-diagenetic changes) must be reconstructed. Examples of this approach are provided by Moretti (2000) and Moretti and Sabato (2007).

4.3 Criteria assessment

If the possible trigger mechanism(s) has (have) thus

been identified, it must be determined whether the SSDS in a specific layer can be attributed to the likely trigger mechanism(s). Relevant criteria should therefore be considered to assess whether the balance of evidence supports the favored trigger; in the case of seismic activity as a presumed trigger, it should be investigated whether the various criteria mentioned above are met, considering all the caveats presented above.

This assessment can be complicated for several reasons. The main reason is that a layer may, before or after being affected by seismic shocks (or both before and after the shocks), be affected by other processes that result in SSDS. Silt-rich, water-saturated lacustrine sediments, which are highly susceptible to deformation by seismic shocks, for instance, are also prone to other deformations. It is, as a rule, difficult to distinguish in such a case between seismically-induced and other SSDS.

4.4 Aspects to be considered

It is worthwhile to emphasize once more that seismites have no specific morphological features and that no specific criteria are available to recognize seismites. It has been suggested, based on the observation of the directional nature of faults and associated seismic waves, that the orientation of SSDS might be a diagnostic feature of a seismic origin (for example, Montenat *et al.*, 2007), but this hypothetical criterion is supported neither by theory, nor by experimental data that are available concerning the effect of seismic waves on a liquefied bed in terms of preferential orientation of SSDS. Observations of present-day seismic liquefaction events (Ninfa *et al.*, 2012; Emergeo Working Group, 2013) show that the elongation of liquefaction features is related only to the facies (particularly grain-size) distribution. Moreover, orientations of SSDS in ancient successions may often depend on the structural (tectonic) development, which makes it even more difficult to distinguish if a preferential orientation of SSDS is related to an endogenic or an exogenic trigger.

5 Concluding remarks

Seismites are probably the most informative record of tectonic/seismic activity in a sedimentary basin. Their recognition, study and interpretation in terms of palaeoseismicity provide data on moderate- to high-magnitude earthquakes. Moreover, analysis of the lateral trends of the frequency, intensity and type of SSDS in a seismite can be used to reconstruct the location of the epicenter and thus of the faults (commonly at some depth in the Earth's

crust) that were responsible for triggering the earthquake and the formation of the SSDS; these SSDS are commonly restricted to an area of roughly 40 km around the epicenter.

It must be realized, however, that the recognition of seismites for palaeoseismic analyses has some limitations. This concerns in particular the areal extent of seismically-induced liquefaction effects, which seems to be strongly controlled by lateral facies changes and hardly has any relationship to the earthquake magnitude. In addition, the actual number of seismic shocks that can be reconstructed from the number of seismites in a sedimentary succession is a complex function of several parameters; this number can be either larger or smaller. The procedures for the recognition of seismites should be largely based on the presence or lack of specific morphological features. In contrast to what is commonly assumed, it seems that no relationship exists between the thickness of seismites and the magnitude of the responsible seismic shocks. No unambiguous relationships exist between the orientation of SSDS in seismites and the orientation of faults.

Finally, we want to stress the importance of sedimentological studies in palaeoseismological analyses. A detailed facies analysis of the entire sedimentary succession involved in the deformation is essential to ascertain which trigger gave rise to the liquefaction process that induced most SSDS in seismites.

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